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SPEED LIMITS OF AIRCRAFT.

By Dr. E. Everling.

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SPEED LIMITS OF AIRCRAFT.*

Introduction.

"Flight means landing" says Siegert. But flight also means speed. It is all the more difficult to reconcile the structural contradiction between great speed and good landing ability, because the requirements have not yet been firmly established and can only be determined with reference to the manner of landing and the nature of the landing field.

This paper is therefore restricted to the question of attainable speed limits and attacks the problem from different angles. A theoretical limit of the maximum speed is obtained from considerations of air resistance above 621 mph 1000 km per hour. According to the present state of engine technics, half of the above is to be regarded as the upper limit. The maximum speed, thus far attained by an airplane, is 341 km (212 miles) per hour, which is already quite near the technical limit. The landing speed, according to tests on models with ordinary wing sections, ranges from 53 km (33 miles) to 75 km (47 miles) per hour, but is still somewhat smaller for actual airplanes.

The actual relation between speed and landing ability is given by statistics of airplanes in dimensionless presentation. The limits are not related according to any rigid law, but a low land-

* Paper read by Dr. E. Everling, June 18, 1922, before the W.G.L. (Scientific Society for Aviation).

ing speed must be obtained at the expense of aerodyramic efficiency.

The selection of suitable wing sections for increasing the maximum speed is facilitated by a new and especially simple abacus, which enables the computation of a series of relations. In particular, it gives from the wing load and the load per HP, the power coefficient, i.e. the D/L ratio divided by the square root of the lift coefficient $(D/L^{3/2})$ and hence the point on the lift curve at which the flight is made. The landing speed must be taken into consideration in determining the wing load.

Ordinary wing sections give, even with low wing loading, quite high landing speeds. "Air brakes" and reversible propellers reduce, it is true, the size of landing field required, but not the landing speed. Adjustable wings are of very little advantage and folding wings add but little to the maximum speed.

Lachmann's slotted wings, which have been tested by Handley Page on an airplane and by a model in the Göttingen aerodynamic laboratory, seem to be the most promising.

The goal of flight technics, namely, ability to land on a small field, requires quite different means. Perhaps the helicopter is destined to help. Light engines are essential, however.

SPEED LIMITS OF AIRPLANES.

(Lecture by Dr. E. Everling)

1. Importance of Large Speed Range.

"Flight means landing" says Siegert, in connection with Baumann's lecture on the economics of air traffic.* The need of being able to compete with other means of transportation, even with inconveniently located airports and against strong winds,** occasions the claims that "Flight means speed."

One of the greatest problems of airplane construction is to reconcile the contradiction between great speed and good landing ability. Efforts have been made to solve it by ordinary technical means and with special devices.

In giving here, at the request of the W.G.L. (Wissenschaftlische Gesellschaft für Luftfahrt), information concerning this work, I am obliged to refrain from any exhaustive treatment of the all too plentiful literature in this field.

I would much rather indicate the present status of the problem, after mentioning the numerical speed limits, by showing statistically what has hitherto been accomplished, what practical limits must be opposed to the theoretical limits, how suitable wing sections for high speeds may be selected, what has been done in the matter of improving the landing speed and what still remains to be done.

* A. Baumann, "Die Kosten der Luftreise," Z.F.M., April 15, 1921, p.98. N.f.L. 21/7, 29 (Nachrichten für Luftfahrer, 1921, No.7, item 29).

** E. Everling, "Der Einfluss des Windes im Luftverkehr," Naturwissenschaften, May 28, 1920, pp. 418-423; "Der Einfluss des Windes auf die Transportleistung," Z.F.M., Feb. 15, 1922, p.40.

2. Maximum Speed.

a) Limit according to the theory of flow.- From the efficiency formula of unaccelerated horizontal flight, the propeller efficiency

$$75 \eta N = W \frac{v}{3.6} = G \epsilon \frac{v}{3.6} \qquad (1)$$

follows for the velocity v (in km/hr; or v/3.6 in m/sec)

$$v = 270 \frac{\eta}{\epsilon} \frac{N}{G} \qquad (2)$$

in which: G denotes the flight weight in kg;

N (HP) or 75 N (kgm/sec) the HP of the engine, hence

G/N (kg/HP) the load per HP;

η propeller efficiency, about 0.67 or 2/3, hence

η N (HP) or 75 ηN (kg/sec) the propeller output and

75 η N/G (m/s) the vertical velocity,*

ϵ the drag-lift ratio (Gleitzahl), the ratio of the drag to the weight G (kg).**

Hence, speed of airplane (m/sec) = vertical velocity divided by the drag-lift ratio,

or, flight speed (km/hr) bears the same relation to 270 km/hr, as the quotient of efficiency divided by the drag-lift ratio to the load per HP.

In order to obtain a pure theoretical upper limit for the

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* Georg König ("Indiziertes Steigvermögen statt Leistuvgsbelastung, Z.F.M., Aug. 31, 1920, pp. 236-237) calls the 75-fold inverse value of the load per HP "indiziertes Steigvermögen" (indicated climbing ability) and, multiplied by efficiency and degree of utilization, "effective Steigvermögen" (effective climbing ability). Our expression "Hubgeschwindigkeit" (vertical velocity) is shorter, more German, and emphasizes "velocity."

** See Table 2, No. 39, Curtiss biplane from the Pulitzer race. The drag-lift ratio is there unfavorable, however.

$\frac{\eta}{\epsilon} = 2.57$; hence $\epsilon \approx \frac{0.7}{2.57} = 0.27 = \frac{1}{3.7}$.

flight speed, we write $\eta = 1$, since the maximum propeller efficiency at high speeds closely approximates this value. For the load per HP, values are known up to 2.43 kg/HP. Here let $G/N = 2$ kg/HP be adopted as the minimum value. There follows for the maximum speed

$$v_g = \frac{135}{\epsilon_k} \tag{3}$$

For the minimum value of the drag-lift ratio ϵ_k, under the assumption that neither parasite drag nor wing-section drag, but only the marginal drag of the wing is present, we obtain*

$$\epsilon'_k = \frac{G}{F\,q}\;\frac{\lambda}{\pi} = c\,A\,\frac{\lambda}{\pi} \tag{4}$$

in which F = wing area in m^2, q = dynamic pressure of the wind in kg/m^2 and λ = aspect ratio of wing (mean chord to span b, or wing area F to b^2). The abstract lift coefficient $c\,A$ is the ratio of the lift A or weight G to the pressure on the wing surface.**

For the aspect ratio $\lambda = 1 : 10 = 0.1$ we would therefore have, as the maximum speed,

$$v_g = \frac{135}{c\,A}\;\frac{\pi}{0.1} = \frac{4240}{c\,A}\ \text{km/h} \tag{7}$$

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* According to L. Prandtl, "Tragflachenauftrieb und -widerstand in der Theorie," Jahrbuch der W.G.L., 1920, p.49, equation 2, we have, for the marginal drag, $W_r = A^2/\pi b^2 q$ and hence, for the drag-lift ratio, $\epsilon_r = W_r/A = A/\pi b^2 q$. The drag-lift ratio, in consequence of the marginal drag, is therefore, the lift divided by the dynamic pressure on the circle with the span as the radius. From this follows equation 4.

** The symbol $c\,A$ is substantiated rather than c_a. E. Everling, "Luftkräfte und Beiwerte," Z.F.M. Dec. 15, 1921, p.340, par. 3. Equation 6 leads moreover to the expression ϵ/cA, while later

$$\frac{\epsilon}{\sqrt{c\,A}} \quad \text{or} \quad \frac{\epsilon}{\sqrt[4]{c\,A}} \quad \text{will appear.}$$

a value, which, for sufficiently small lift coefficients, can grow into infinite, though fabulous, wing loads, near the ground,* on account of equation 7),

$$\frac{G}{F} = c\ A\ q = \frac{c\ A}{16}\ v_g{}^2 = \frac{4240}{16}\ v_g = 265\ v_g\ \mathrm{kg/m^2} \qquad (8)$$

Hence no upper limit can be obtained** in this manner, even by solving equation 8 according to v_g.

Useful results came from the assumption that only the parasite drag of a fuselage for passengers and power plant exists. If the cross-section of this fuselage f is called its coefficient of drag (ratio of drag W to dynamic pressure q on f), $c\ W_f = 0.05$ and we have, for the flight performance,

$$75\ \eta\ N = W\ \frac{v}{3.6} = c\ W_f\ \frac{f}{16}\ \left(\frac{v}{3.6}\right)^3 \qquad (9)$$

Since a 1000 HP engine can be easily brought within one sq.m. of front surface area, $N/f = 1000\ \mathrm{HP/m^2}$ is not too favorable and may therefore

$$v_g = 3.6\ \sqrt[3]{75\ \eta\ \frac{16}{cW_f}\ \frac{N}{f}} = 3.6\ \sqrt[3]{75 \times 1.00\ \frac{16}{0.05}\ \frac{N}{f}} =$$

$$= 103.8\ \sqrt[3]{\frac{N}{f}} = 1038\ \mathrm{km/h} = 288\ \mathrm{m/s} \qquad (10)$$

be regarded as a sort of upper limit.

*Air density designated by $0.125\ \mathrm{kg^2/m^4}$, hence half the air density = $1/16\ \mathrm{kg^3/m^4}$.

** This is comprehensible, if we remember that the parabola of the marginal drag, in Lilienthal's lift curve has the axis of the lift coefficient at the zero point for tangent. On the other hand, L. Prandtl, in Luftfahrt, May, 1921, p.83, gives a formula for the minimum power of airplanes for a desired speed without deduction. This equation, which follows from our equation 1 by solving according to N and introducing W according to equation 5, occasioned the remarks in the paragraph in small type. It could not be simply inverted, because it was sought to determine the speed limit for any horsepower.

b) Limits according to technical considerations.- While theoretical considerations seek to outline the field of possible limits according to physical laws, technical considerations give limits, which, in the present status of engine construction, cannot be exceeded.

Rateau* takes

$$\eta = 0.75$$

$$\frac{G}{N} = 3.5 \text{ kg/HP and}$$

$$\epsilon = \frac{1}{8} = 0.125, \text{ hence}$$

$$\frac{\eta}{\epsilon} = 0.75 \times 8 = 6.0 \qquad (11)$$

a value which, so far as I know, has only been exceeded by one airplane.** There follows, for the maximum speed according to equation 2,

$$v_g = 270 \frac{6.0}{3.5} = 463 \text{ km/h} = 129 \text{ m/s} \qquad (12)$$

Near the ground, this corresponds to $129^2/16 = 1030$ kg/m² dynamic pressure, hence about 500 kg/m² wing load, or about one-tenth of the usual cross-sectional area and about six times the maximum value at that time.** Although this maximum wing load occurs on the same airplane, which, on account of its favorable flow characteristics, has a better drag-lift ratio than here

* A. Rateau, "Sur les plus grandes distances franchissables par les avions et les plus grandes vitesses realisables" (Maximum flight distances and speeds), Comptes Rendus, Feb. 16, 1920, pp. 364-370; Z.F.M. July 15, 1920, p.196.

** For the 1000 HP Staaken monoplane, $\eta/\epsilon > 7$ (See table 2, No. 38). Wing load is $G/F = 80$ kg/m²; load per HP is high, $G/N = 6.5$ kg.

adopted, it is nevertheless to be expected that, with a still greater wing load, the parasite drag will preponderate and accordingly reduce π/ϵ of equation 11, and hence also the maximum speed, to a value estimated at 4. On the other hand, the load per HP can be reduced. If it is set, as above, at $G/N = 2$ kg/HP, we have

$$v_g = 270 \frac{4.0}{2.0} = 540 \text{ km/h} = 150 \text{ m/s} \tag{13}$$

which would be about the upper limit in the present state of the science.

c) Speed records.- In comparison with these computations, what has actually been attained?

1.	The speed record* stands at	341 km/h	or	95 m/s	
2.	Official speed record**	330 "	"	92 "	
3.	Rateau's formula	463 "	"	127 "	
4.	Our technical computations	540 "	"	150 "	
5.	Our flow computations	1038 "	"	288 "	

We are therefore not so very distant from the technically possible limit of the maximum speed, having attained 3/4 of Rateau's maximum value or 2/3 of our value, and will in fact probably get no higher, because the drag-lift ratio of racers is poor. Contrary to the general opinion, we would emphasize the fact that,

* Speed record of the Englishman, James, on a Mars Bamel racer of the Gloucestershire Aviation Company, with a 450 HP Napier Lion engine at Mattlesham, Dec., 1921, the average speed for the whole distance being 316 km/hr or 88 m/s. Source: N.f.L. 22/2,4 (Nachrichten fur Luftfahrer, 1922, No. 2, item 4); Luftweg, Jan. 24, 1922.

** From the FAI official record of Sadi Lecointe on a 300 HP Nieuport Delage, Sept. 26, 1921. Source NfL, 22/9, 2, last line of table.

in the future, it will be the province and duty of aerodynamics to increase the maximum speed.

d) Results.- The economical and practical aspects of carrying and landing ability set, however, a far lower limit to the maximum speed, than that technically possible. A greater carrying capacity increases the load per HP and consequently reduces the speed, so long as the engines are not lighter or more economical, in like measure. The endeavor after a lower landing speed leads to the choice of wing sections with a poorer drag-lift ratio (D/L).

3. Landing Speed.

Here aerodynamics must help. The landing speed limits must be first calculated and compared with the landing speed already attained.

a) Minimum speed limit with model.- The flight speed is at the minimum v_k (km/h), when the lift coefficient attains its maximum value for $c\ A_g$, hence near the ground* according to the definition of $c\ A$, equation 4 or 8,

$$v_k = 14.4 \sqrt{\frac{G}{F}} \frac{1}{\sqrt{c\ A_g}} \qquad (14)$$

hence proportional to the square root of the wing load G/F (kg/m²) and of the reciprocal of the maximum lift coefficient $c\ A_g$.

Table 1 contains several measurements, obtained with models, of especially large lift coefficients, with notation of source.**

* Air density designated by 0.125 kg³/m⁴, hence half the air density = 1/16 kg³/m⁴.

** Max Munk und Erich Hückel, "Der Profilwiderstand von Tragflügeln," Technische Berichte, Aug. 1, 1918, pp. 451-461, especially p. 458, column B_o.

Also the quantity $1/\sqrt{c\ A_g}$, which gives the landing speed for the model, when multiplied by $14.4\sqrt{G/F}$, hence, for example, for the wing loads 25, 36, 49, 64, 81 and 100 kg/m² multiplied by 72, 86.4, 100.8, 115.2, 129.6 and 144 respectively, (the minimum drag coefficient c w k being added).

The maximum value of table 1 for ordinary wing sections ($c\ A_g = 1.805$) gives for wing loads of 25 and 49 kg/m², 54 and 75 km/hr, respectively. Any diminution of the wing load is made at the expense of speed and works according to the square root of G/F.

b) Influence of scale of model.- Results obtained with models cannot be transferred directly to full-sized airplanes. The Reynolds number is generally greater in flight than in the wind tunnel and hence the flow conditions are changed. Moreover, the shape of actual wings does not correspond to the cross-section of the model. Lastly, good wind tunnels are not so turbulent as the atmosphere.

Experiments with models therefore give too small a maximum lift. For not too thick wing sections, the lift is directly proportional to Reynolds number. For very large angles of attack the flow shifts, as shown both by experiments with models* and during flight.** The increase in lift for a large airplane, in

* L. Prandtl, C. Wieselsberger und A. Betz, "Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen," Report I, Chap. IV, 2, "Der Einfluss des Kennwertes auf die Luftkräfte von Tragflügeln" pp. 54-62; also N.f.L. 22/8, 14.

** See N.f.L. 22/9, 13, "$c\ A_g = 2.34$ beim Flugzeug, gegen 2.07 beim Modell"; N.f.L. 22/7, 21, "Auftrieb beim Flugzeugversuch wie beim Modell"; N.f.L. 21/51, 30 (the same for Fok D VII) and 21/20, 34, "Strömung schlägt bei grossen Flugzeugen erst mit höherem Anstellwinkeln um"; 20/7, 4, "$c\ A_g$ beim grossen Flugzeug höher."

comparison with the model, is estimated at about 0.05.

c) Influence of nearness of ground.- For the same value (0.05), the maximum lift may be considered greater, when the airplane is near the ground. According to experiments with models* and during flight,** the lift increases, in harmony with computation, as much as 10% of its value in free air. If we, accordingly, call the lift coefficient of an airplane near the ground 10% greater than that of a model, we obtain, according to equation 14, 5% smaller landing speeds.

d) Observed landing speeds.- In comparing computations on the basis of wind tunnel experiments, the c_{A_g} values are therefore increased by 0.1 and also, on account of the influence of the ground, the minimum speeds measured in free air are diminished by about 0.05 in the transition to landing speeds.

On the other hand, a contrary wind has a much greater effect on experiments at low speeds than at maximum and mean flight speeds. The experimental values of landing speeds are therefore much too favorable. Moreover, the gliding before landing is no permanent condition.*** Thereby mechanical energy is also destroyed. But in the last instant before landing, if one does not plunge into the ground, he must pass through the angle of attack of maximum lift. These tendencies offset one another partially, so that observation

* See N.f.L. 22/10, 16, "Grösstauftrieb nur wenig verbessert"; N.f.L. 21/27, 34, "Auftrieb steigt, Widerstand sinkt um Beträge bis zu 0.10"; N.f.L. 21/25, 29, C. Wieselsberger, "Uber den Flügelwiderstand in der Nähe des Bodens"; Z.F.M. May 31, 1921, pp.145-7, "Hochstauftrieb wenig vergrössert"; N.f.L. 21/9, 52, "Auftrieb steigt um rd 0.06).

** See N.f.L. 22/9, 13.

*** A Pröll, "Über die Wahl der Flächenbelastung mit besonderer Rücksicht auf den Laudungsvorgang," Z.F.M., Oct. 31, 1920, pp. 277-281.

and computation agree quite well here.

4. Speed Limits of Actual Airplanes.

What relation do the facts bear to these speed limits? Table 2 gives airplane speed statistics whic may be considered as reliable.

a) Scope of statistics.-* More than half the accumulated material had to be eliminated at the outset, because the sources seemed unreliable or the computation gave impossible coefficients. Of the 43 selected data, one or the other may still be incorrect, but it cannot vitiate the result, since it does not fall outside the field of the others.

On the other hand, useful data may have escaped our notice. I would be especially grateful for any such data for supplementing table 2.

b) Method of presentation.- In order to be able to compare the speed limits of widely differing airplanes, not these themselves but abstract members were assembled (See Fig. 1, and table 2) The airplanes are arranged according to increasing landing speed (in a few cases computed by subtraction of 0.05 of the value from the minimum speed) and for the same landing speed according to the decreasing maximum speed.

There were computed and set down the abstract values

$$\frac{v_k}{3.6 \times 4}\sqrt{\frac{F}{G}} = \frac{v_k}{14.4} : \sqrt{\frac{G}{F}} = \frac{1.05}{\sqrt{c\ A_g}} = \text{Landing coefficient} \qquad (15)$$

$$\frac{v_g}{3.6 \times 75}\ \frac{G}{N} = \frac{v_g}{270}\ \frac{G}{N} = \frac{\eta}{\epsilon\ F} = \text{Speed coefficient} \qquad (16)$$

*Most of the data were taken from the N.f.L. and its predecessors, "Flugarchiv" (1920, partially reproduced in the 1920 ZFM) and "Luftfahrt-Rundschau" (ZFM 1919, the technical portions of which were edited by me.)

Equation 15 follows from equation 14. The quantity 1.05 on the right side refers to the lift increase of the airplane near the ground in comparison with the result obtained from the model. Equation 16 is derived from equation 2. ϵF is the drag-lift ratio for the angle of flight.

Fig. 1 shows, as the second division on the horizontal axis, the value $c\ A$; on the vertical axis, the value

$$\frac{1}{\epsilon} = \frac{A}{W} = \frac{c\ A}{c\ W} \text{ for } \eta = 0.70$$

The bundle of lines from the zero point correspond to like values of the expression

$$\frac{v_g}{v_\kappa}\ \frac{4}{75}\ \frac{G}{N}\sqrt{\frac{G}{F}} = \frac{\eta}{1.1}\ \frac{\epsilon\ F}{c\ A_g} = \frac{\eta}{1.05}\ \kappa F\sqrt{\frac{c\ A_F}{c\ A_g}} \tag{17}$$

according to which

$$\kappa = \frac{\epsilon}{\sqrt{c\ A}} = \frac{c\ W}{c\ A^{1.5}} \tag{18}$$

an important value for flight with constant propeller efficiency,* for which we propose the term "Flugzahl" (power coefficient**). In fact, it gives the momentary flight condition. If we write both equations 15 and 16 for the flight speed $v\ F$, we will have instead of equation 17

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*First probably by Raoul J. Hofmann, "Der Flug in grossen Höhen," ZFM, Oct. 11, 1913, pp. 255-256, especially equation 3.

**Mostly the less convenient value $1/\kappa^2 = cA^3/cW^2$ is used and often termed "Steigzahl" (coefficient of climb). The question however does not concern climbing, as shown by equation 19, but flight and the deduction (descending speed!) in climb computations. H. v. Sanden ("Die Bedeutung von $ca^3/c_W{}^2$" T B III, 1918, pp. 330-1) recommends instead, with reference to change of efficiency with speed, $c\ A^{2.5}/c\ W^2$, which gives

$$\kappa = \frac{c\ W}{c\ A^{1.25}} = \frac{\epsilon}{\sqrt[4]{c\ A}} \tag{19}$$

$$\frac{4}{75\,\eta}\ \frac{G}{N}\sqrt{\frac{G}{F}} = \kappa \qquad (20)$$

c) Results - Limit curves.- The points for the various airplanes generally lie in a bunch, so that it is impossible to draw any curve through them.

Especially high and aerodynamically favorable are the two German traffic airplanes, the Staaken monoplane and the Sablatnig P_3. The folding-wing airplane of Gastambide-Levasseur presents the best landing characteristics (even aside from its increased wing area), if we may trust the data, though the reasons are not apparent. The old English biplanes of 1912 lie rather far to the right. The poorest of all is a heavily loaded Curtiss boat seaplane, though it makes a better showing with a smaller weight. Of two otherwise similar Curtiss airplanes, the biplane is aerodynamically better than the triplane, though both land equally well. The limiting of the group of points to the left and top by a curve (dash line in Fig. 1) is rather bold, since airplanes with alleged good landing ability were eliminated as doubtful, though the inclination of the curve shows that a large $c\,A_g$ can only be obtained at the expense of otherwise good flow characteristics.

d) Estimation of the speed range.- Even when neither the group of points nor the boundary curve shows any legitimate connection, there must nevertheless be some order of ranking airplanes according to their speed.

Fig. 1 gives curves which run parallel or nearly parallel to the boundary line. They are not quite accurately enough deter-

mined. They correspond to the ratio of the landing coefficient to the speed coefficient, in that they pass through the zero point and intersect the boundary curve rather bluntly, but show, however, that this ratio cannot exceed a certain magnitude of the individual values.

Practice demands, independently of the maximum speed, a definite landing speed, which cannot be exceeded, if the airplane is to be capable of being used on the landing places provided. For swift airplanes, however, better landing places can be provided at greater intervals. For racing purposes, a good starting track is sufficient.

Evidently, the different viewpoints lend themselves just as poorly to any computation formula or to a set of curves of like speed values, as is possible for the mutual estimation of carrying capacity and speed. In contests, we must proceed more or less arbitrarily, according to practical experience and requirements or allow the contestant the choice of various determining factors.

5. Increasing the Maximum Speed.

The problem is to increase the maximum speed without increasing the landing speed, or still better, to reduce the latter at the same time.

a) Abacus for lift curve ("Polar"). - According to equation 3 the speed for a given flight condition is obtained from the vertical velocity and the drag-lift ratio. The angle of attack follows,

The line and the parabola from the zero point, which just touch the lift curve, give the best drag-lift ratio and the smallest power coefficient. All other straight lines and curves have two points of intersection with the lift curves.

The lift curve must be shifted sidewise with its zero point, as far as the c W value of the abacus, which corresponds to the parasite drag of the airplane with reference to the wings.

b) Determination of drag-lift ratio, power coefficient and maximum speed.-* The abacus in Fig. 2 solves graphically equations 20 and 2. We first find the drag-lift ratio and power coefficient, for any angle of attack, from the straight lines or parabolas passing through the corresponding point of the lift curve (values read on the middle scale).

In practice, it is better to find the angle of attack and speed of an actual airplane, i.e. for a given load per HP (upper horizontal line, lower scale). A straight line through the proper points of the scales intersects the middle scale at the point of the desired coefficient of power. The intersection of the corresponding parabola with the lift curve gives the angle of attack, coefficient of lift and coefficient of drag. A line through the zero point and this polar point enables the reading of the drag-lift ratio on the middle scale. If this is combined with the value of the load per HP (upper horizontal line, lower scale), the flight speed is intersected on the oblique line (lower scale). For any given load per HP, it is inversely proportional to the drag-lift ratio.

c) Choice of wing section.- For a given lift curve, the wing

*The use of the abacus for finding ascending and descending speeds, as well as for other purposes, with reference to altitude and air density, efficiency and aspec ratio, will shortly be described in the ZFM. In this connection, we are only considering the speed.

load and load per HP should be so chosen for the maximum speed that the power coefficient curve will pass through the contact point of a tangent to the lift curve from the zero point, thus enabling flight with the best drag-lift ratio. Then the inclination of this tangent is decisive between two wing sections.

If, however, the power coefficient is fixed, the lift curve, which intersects the parabola farthest to the left, gives the maximum speed.

The graphic selection is so convenient that it seems useless to seek for mathematical solutions (such as replacing the lift curve by a parabola), so long as the shape of the wing section cannot be connected analytically with the course of the lift curve.*

d) Choice of wing load.- From Fig. 2 it follows that a high maximum speed must be obtained through high wing loading. On the contrary, landing requires a small wing load. Here it is generally more difficult to give the correct value, in proportion as the requirements for the speed limits are not well established. Pröll** gave, for the maximum speed and for the landing speed and also for gliding, curves and computation methods, which clearly explain the process of landing. Our abacus could also serve the same purpose.

The power coefficient parabola through the zero point on the

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*Mention should, however, be made of a graphic-mathematical process for choosing a wing section, N.f.L. 22/11, 28, Edward P. Warner, "The choice of wing sections for airplanes," N.A.C.A., Technical Note No. 73, November, 1921.

**A. Pröll, "Über die Wahl der Flächenbelastung mit besonderer Rücksicht auf den Landungsvorgang," ZFM, Oct. 31, 1920 pp. 277-281.

lift curve gives, with the load per HP, the most favorable wing load for the maximum speed. If the wing area differs much from the first assumption, the parasite drag must sometimes be corrected by shifting the lift curve correspondingly and correcting the calculation. If the lift curve is drawn on transparent paper and laid over the abacus, this is easily done.

6. Reducing the Landing Speed.

Though the maximum speed, without regard to economy, may be quite easily increased, the landing speed limit, by ordinary means, has been reached. Most wing sections with high lift have a large drag (See table 1). Over $c\ A_g = 1.81$ has not been obtained.* Search has therefore been made for special devices for reducing the speed just before coming in contact with the ground.

a) Air brakes and reversible propellers.- Just as in taxying on the ground, the use of devices, such as air brakes** and reversible propellers, for increasing the parasite drag while still in the air, enables the shortening of the requisite landing distance.***

The landing speed, i.e. the speed at the instant of touching the ground, and hence the danger of upsetting, can be lessened,

*C. Wieselsberger remarked that the maximum lift evidently depends largely on the vortex condition of the air stream and next on the exactness of the model.
**"Luftbremsen fur Flugzeuge" (Air brakes for airplanes), ZFM, Jan. 31, 1920, p. 30.
***Report of H. Glauert "Über das Landen von Flugzeugen" (Landing of airplanes), N.f.L. 21/47, 38.

however, not by increasing the drag but only by increasing the lift. Hence, retarding devices do not enter into our problem, but rather lifting devices.

b) Shifting the wing section.- By increasing the camber,* best by a simultaneous lowering of both the leading and the trailing edge,** the wing load* may be increased up to 35% for the same landing speed,*** but the increase in the weight of the wings and the weight of the warping mechanism* and the shifting of the center of pressure**** nullifies these advantages. Flexible ribs are structurally difficult and unsafe,* but enable nearly as great improvement.***

We have no reliable data on the actual weight and speed relations of airplanes with adjustable wing section. We must therefore await the results of technical investigation, without being too sanguine.

c) Increasing the wing area.- On account of the marginal drag, folding wings of maximum span and small area are better for swift flight and hence in landing they should be extended forward and backward, instead of laterally.***** The weight of the wings

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*Views of W. H. Sayers, N.f.L. 21/29, 21. Also remarks of C. R. Fairey, (Fairey seaplanes with a wing load of 60 kg/m^2 have successfully alighted on water, due to their wing flaps ("Profilklappen").

**"Luftbremsen für Flugzeuge" (Air brakes for airplanes), ZFM, Jan. 31, 1920, p. 30.

***H. Hermann, "Verstellprofile" (Flexible wing sections), ZFM, May 31, 1921, pp. 147-154, especially Figs. 4 & 5, tables 4 & 9, Parker wing section with flexible ribs.

****Report of H. Glauert, "Über das Landen von Flugzeugen" (Landing of airplanes), N.f.L. 21/47, 38.

*****Gastambide-Levasseur biplane (Table 2, No.1), N.f.L, 21/27, 38. The upper wing is made twice as broad (3.28 instead of 1.6 m.) thereby increasing its area from 32 m^2 to 52 m^2, or 1.6-fold.

is, however, more than half again as great* as that of adjustable wing sections, and hence the chances of success are poorer.

The landing speed is affected in like degree (equation 14) by the lift coefficient and by the wing load. While a greater maximum lift unfits a wing section for swift flight, the maximum speed is only slightly increased by employing folding wings and for small powers it is even decreased. This was done by Lupberger** under the here fairly justified assumption that the parasite drag is independent of the wing area.*** This follows also from the abacus (Fig. 2), though not just the same as Lupberger's approximation. The power coefficient varies as the square root of the wing load, though the corresponding drag-lift ratio, on account of the flexure of the lift curve, varies much less, even when the lift curve is shifted toward the left, for a small wing load, in order to make allowance for the relatively small drag coefficient.

Folding wings must be rejected, chiefly because the 1.8-fold increase of area, technically a very difficult task, only reduces the landing speed one-fourth, not to mention the increase in weight.

*Views of W. H. Sayers, N.f.L. 21/29, 21. Also remarks of C. R. Fairey (Fairey seaplanes with a wing load of 60 kg/m² have successfully alighted on water, due to their wing flaps "Profilklappen").

**E. Lupberger, "Über den Einfluss der Flügelabmessungen auf die Fluggeschwindigkeit," ZFM, Nov. 15, 1921, pp. 316-318.

***With the drag area $f(m^2)$ and the parasite drag coefficient $c\,W_f$, Lupberger makes $f\,c\,W_f = 1.2\ m^2$. We must therefore make $c\,W_s = \frac{1.2}{F}$. Moreover, Lupberger considers the wing section drag as constant, hence the lift curves as parabolas.

d) Slotted wings.-* Lachmann's invention, which, independently of him, Handley Page tested, both on a model and on a full-sized airplane, offers the best prospects (Table 1, Nos. 7-10). The maximum value $c\ A_g = 3.92$, corresponds, for 25 and 49 kg/m^2 wing load to the respective landing speeds 36 and 51 km/hr, with respect to the size of the airplane and the nearness to the ground, 35 and 48 km/hr. For the maximum value of the German measurements, the figures are $c\ A_g = 2.19$, $v_k = 49$ and 68 km/hr and 46 and 65 km/hr, respectively.

We must await the confirmation of the high value of the English measurements and information as to how much the result was affected (presumably favorably) by the turbulence, which is not always present; as to how far it is possible to retain the good qualities of the wing with closed slots, to combine rigidity, light weight and reliability in multiple slotted wings, with their many shutters; and to admit of an angle of attack of 45°, without excessively heavy landing gear and complicated wing controls.

7. Future Development.

However promising these means for increasing the speed range may seem to the hopeful inventors, we must not forget that, at best, the ground must be encountered, in landing, at the maximum speed of our street vehicles, if the airplane is suited in other respects for air traffic.

*N.f.L. 21/26, 33-35. C. Wieselsberger, "Untersuchungen über Handley Page Flügel" (Mitteilungen der Aerodynamischen Versuchsanstalt zu Göttingen, III Folge, No.3), ZFM, June 15, 1921, pp.161-164; G. Lachmann, "Das unterteilte Flächenprofil," idem, pp.164-169.

The goal lies, however, much nearer - and yet, at the same time, very far. "To fly safely and efficiently means to land on the spot." None of our roads leads there. Shall not the helicopter give us the solution? And here aerodynamics turns again to engine constructors with the demand for light and reliable engines.

Translated by
National Advisory Committee
for Aeronautics.

Table 1. Maximum lift coefficient obtained by experimenting with models.

No	Wing section	Source	c_{A_g}	$\frac{1}{\sqrt{c_{A_g}}}$	c_{W_k}	Remarks
1	Göttingen 227	TB II (Munk and Hückel) S. 430	1.679	0.77	0.038	
2	" 234	S. 437	1.790	0.75	0.052	
3	" 242	S. 432	1.739	0.76	0.039	
4	" 244	S. 432	1.805	0.74	0.072	
5	Avro:	NfL 22/4, 33	1.92	0.72	--	
6	Glenn L. Martin	NfL 21/13,38	2.03	0.70	--	
7	Eng. propeller 4	NfL 21/50,34	2.51	0.63	--	Handley Page, with 2 slots.
8	Handley Page	NfL 21/11,41	3.92	0.51	--	With 6 slots, angle of attack 45°.
9	"Handley Page"-Göttingen	ZFM 12, pp. 161-162	1.963	0.71	0.0358	1 slot, drag not constant
10	Lachmann (Göttingen 422)	ZfM 12, p. 166	2.19 (1.38)	0.68 (0.85)	0.044 (0.020)	6 slots (bzw. (2) Profil)
11	Albatros-DD	NfL 22/10,27	1.72	0.76	--	Leading and trailing edges shifted.

Table 2. Speed limits of actual airplanes arranged according to landing speeds.

No.	Airplane Maker, designation, purpose, material.	Source NfL* or "Flug-archiv"	Landing maximum speed v_k km/hr	v_k mi/hr	v_g km/hr	v_g mi/hr	Wing load G/F kg/m²	G/F lb/ft²
1	Gastambide-Levavasseur-ED	21/27,38	48	29.83	200	124.27	27.1 (44.0)	5.55 (9.01)
2	Sperry-"Messenger" DD	21/13,49	57	35.42	150	93.21	25.0	5.12
3	M. Farman-DD of 1912	22/15,21	60	37.28	89	55.30	14.3	2.93
4	Laird-"Swallow"-DD	21/ 1,49	61	37.90	139	86.37	26.3	5.39
5	Waterman-Sport-DD "30 x 100"	21/24,23	(62)	38.52	145	90.10	25.6	5.24
6	BE 2 ("British Experimental")-DD of 1912	22/15,21	64	39.77	113	70.21	22.5	4.61
7	Avro-"Baby"-DD "No. 543"	20/12,06	65	40.39	132	82.02	26.8	5.49
8	Curtiss "IN" with Sperry-ED-Flügel	21/26,32 21/51,36	68	42.25	137	85.13	38.3	7.84
9	Orenco-Jagd-DD"B"	1911	69	42.87	200	124.27	35.3	7.23
10	Fokker-Express-DD "C II"	21/22,29	73	45.36	186	115.57	43.8	8.97
11	Lincoln-"Normal"-DD	3902	73	45.36	170	105.63	30.3	6.21
12	Vought-School-DD "VE 7"	20/11,11	73	45.36	167	103.77	32.8	6.72
13	Orenco-Touring"F"	1911	73	45.36	150	93.21	34.1	6.98
14	Stout-"Bat Wing" Commercial-ED	21/ 3,35	75	46.60	194	120.55	45.2	9.26
15	Orenco-Pursuit-DD "D"	1911	76	47.22	224	139.19	45.8	9.38
16	Aeromarine-Boat-Seaplane "6 FsL"	3410	76	47.22	130	80.78	45.2	9.26
17	Handley-Page Giant airplane "V/1500"	Lu 0207	78	48.47	160	99.42	49.0	10.04
18	Handley-Page Giant airplane "O/400"	Lu 0207	78	48.47	151	93.83	49.1	10.06
19	Cody-DD of 1912	22/15,21	78	48.47	117	72.70	27.4	5.61
20	Avro-Manchester-Commercial-DD"II"	2118	80	49.71	261	162.18	41.3	8.46
21	Vikers-"Viking"-Amphibian-DD	21/19,41	80	49.71	193	119.92	46.3	9.48

*NfL stands for Nachrichten fur den Luftfahrer, Numbers - year - No. Item N - 4-figure numbers: "Flugarchiv" 1920, partly reprinted in 1920 ZFM. "Lu" stands for Luftfahrt-Rundschaus of the ZFM 1919 (Nos. 17-24).

Table 2 (Cont.). Speed limits of actual airplanes arranged according to landing speeds.

No.	Airplane Maker, designation, purpose, material.	Source NfL*or "Flug-archiv"	Landing v_k km/hr	Landing v_k mi/hr	maximum speed v_g km/hr	maximum speed v_g mi/hr	Wing load G/F kg/m²	Wing load G/F lb/ft²
22	Junkers-commercial -ED	21/17,56 21/28,50	(80)	49.71	180	111.85	45.6	9.34
23	US-Boeing armored twin-engine-DrD "GAX"	21/22,32 22/17,15	80	49.71	170	105.63	46.7	9.57
24	BAT-"Basiliske"-1-seat pursuit-DD "FK 25"	21/50,16	82	50.95	238	147.89	44.4	9.09
25	Glenn-Martin-twin-engine freight-DD	21/ 6,40	84	52.20	178	110.60	52.6	10.77
26	Fokker-Pursuit-DD "D VII"	21/33,27	(87)	54.06	193	119.92	45.4	9.30
27	Armored Infantry-ED "IL 12"	21/52,16	90	55.92	230	142.92	58.6	12.00
28	Orenco Pursuit-DD "D_2"	1911	91	56.54	250	155.34	50.3	10.30
29	Curtiss-Mail-DD "HA"	20/05,06	91	56.54	201	124.90	40.7	8.34
30	Curtiss-DD } otherwise similar	22/	93	57.79	262	162.80	45.8	9.38
31	Curtiss-DrD } otherwise similar	22/	95	59.03	258	160.31	47.3	9.69
32	Sablatnig commercial-DD "P3"	Seehase	95	59.03	149	92.58	50.0	10.24
33	Deperdussin-ED of 1912	22/15,21	95	59.03	111	68.97	30.0	6.14
34	Hanriot-ED of 1912	22/15,21	96	59.65	121	75.19	31.6	6.47
35	Watermann-racer-ED	21/34,31	97	60.27	209	129.87	49.6	10.16
36	Supermarine-"Baby"-1-seater military boat-seaplane"AD"	1121	87	54.06	178	110.60	36.5	7.48
37	Glenn-Martin twin-engine bomber	2910 22/11,25	97	60.27	172	106.88	52.8	10.81
38	Curtiss-Boat seaplane "NC4"	Lu 0304	102	63.38	156	96.93	49.7	10.18
39	Staaken-1000 HP commercial-DD	Rohrbach	110	68.35	227	141.05	80.0	16.39
40	Curtiss-racer-DD	21/52,14	112	69.59	285	177.09	63.2	12.94
41	Curtiss-Boat seaplane "NC4",	Lu 0304	137	85.13	167	103.77	57.8	11.84
42	American Boat seaplane "HS-1L"	0505	95	59.03	164	101.90	43.7	8.95
43	American Boat seaplane "HS-2L"	0505	99	61.52	164	101.90	37.6	7.70

*See p. 25.

Table 2 (Cont.). Speed limits of actual airplanes arranged according to landing speeds.

No.	Load per HP		Coefficient of	
	G/N kg/PS	G/N lb/HP	Landing speed $\frac{v_k}{3.6\times4}\sqrt{\frac{F}{G}} = \frac{1}{\sqrt{1.1\ c_a}}$	Maximum speed $\frac{v_g}{3.6\times75}\ \frac{G}{N} = \frac{\eta}{\epsilon}$
1	5.62	12.39	0.64	4.16
2	6.22	13.71	0.79	3.46
3	12.20	26.90	1.11	4.02
4	8.89	19.60	0.83	4.57
5	9.10	20.06	0.85	4.89
6	10.70	23.59	0.94	4.48
7	11.0	24.25	0.87	5.38
8	7.15	15.76	0.77	4.38
9	3.62	7.98	0.81	2.67
10	6.37	14.04	0.77	4.38
11	5.90	13.01	0.92	3.71
12	6.07	13.38	0.89	3.76
13	7.40	16.31	0.87	4.11
14	7.60	16.76	0.77	5.46
15	3.67	8.09	0.78	3.04
16	6.82	15.04	0.79	3.29
17	9.09	20.04	0.77	5.37
18	8.46	18.65	0.84	4.74
19	10.80	23.81	1.04	4.68
20	5.30	11.68	0.86	5.11
21	4.93	10.87	0.83	3.53

Table 2 (Cont.). Speed limits of actual airplanes arranged according to landing speeds.

No.	Load per HP G/N kg/PS	G/N lb/HP	Coefficient of Landing speed $\frac{v_k}{3.6 \times 4}\sqrt{\frac{F}{G}} = \frac{1}{\sqrt{1.1\, c_a}}$	Maximum speed $\frac{v_g}{3.6 \times 75}\frac{G}{N} = \frac{\eta}{\epsilon}$
22	7.20	15.87	0.82	4.79
23	5.15	11.35	0.81	3.24
24	2.87	6.33	0.86	2.53
25	6.80	14.99	0.81	4.48
26	4.62	10.19	0.90	3.30
27	5.68	12.52	0.82	4.82
28	3.60	7.94	0.89	3.33
29	4.58	10.10	0.99	3.41
30	3.31	7.30	0.96	3.20
31	3.40	7.50	0.96	3.26
32	10.20	22.49	0.93	5.62
33	10.60	23.37	1.21	4.36
34	10.90	24.03	1.18	4.89
35	5.69	12.54	0.96	4.40
36	7.07	15.59	1.00	4.65
37	6.85	15.10	0.93	4.37
38	6.81	15.01	1.01	3.94
39	8.50	18.74	0.86	7.14
40	2.44	5.38	0.98	2.58
41	7.94	17.50	1.25	4.91
42	8.05	17.75	1.00	4.98
43	8.48	18.70	1.12	5.14 ?

Table 2 (Cont.). Speed limits of actual airplanes arranged according to landing speeds.

No.	Wing section	Speed trial	Remarks.
1	Sonderform		Adjustable wings.
2	USA 15	Amer. H.-V.-A.?	
3	---	Eng. contest or race	
4	RAF 15	?	V_k computed from 65 km/hr minimum speed.
5	USA 27	?	
6	---	Eng. contest or race	
7	RAF 15	?	
8	Sperry	Amer. H.-V.-A.?	
9	---	?	
10	Fokker	?	
11	RAF 32	?	
12	Vought 6	?	
13	---	?	
14	Sonderform	?	
15	---	?	
16	---	?	
17	---	?	
18	---	?	
19	---	Eng. contest or race	
20	---	?	
21	---	?	

Table 2 (Cont.). Speed limits od actual airplanes arranged according to landing speeds.

No.	Wing section	Speed trial	Remarks
22	Junkers	Amer. flying forces	v_k computed from 84 km/hr minimum speed.
23	---	Amer. H.-V.-A.?	
24	---	?	
25	Albatros	?	(See 38)
26	Fokker	Amer. H.-V.-A. with 400 HP Liberty	v_k computed from 91.5 km/hr minimum speed
27	---	?	
28	---	?	
29	Sloane	Curtiss?	
30	---	?	
31	---	?	
32	Sablatnig	DVL	
33	---	Eng. contest or race	
34	---	Eng. contest or race	
35	USA 15	?	
36	---	Amer. Mar.?	
37	---	?	(See 25)
38	RAF 6	Amer. Mar.?	(See 43)
39	Staaken	DVL	v_g computed for 1450 r.p.m.
40	---	Pulitzer contest or race	
41	Wie 40	Wie 40	(See 40)
42	---	Amer. Mar.?	(See 39)
43	---	Wie 33	(See 33)